46TH TURBOMACHINERY & 33RD PUMP SYMPOSIA
HOUSTON, TEXAS | DECEMBER 11-14, 2017
GEORGE R. BROWN CONVENTION CENTER

SUPERIMPOSING PLANETARY GEARS AS VARIABLE SPEED DRIVES FOR ROTATING EQUIPMENT

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ABSTRACT

There are many high-power and high-speed pumps installed in power plants, oil & gas applications and in petrochemical industry consuming a considerable amount of energy. Significant interest exists within operators to improve their efficiency in order to save energy and operating cost. Most of the pumps are driven by electric motors and many of them are speed controlled since this is the most efficient method to adjust flow to process demand. Motor speed is controlled by frequency converters which are installed in-line and therefore they are of full scale and designed to full power. The complete power goes through the variable frequency drive and is subject to losses. A gear then is used in order to step-up motor speed to the requested speed level for the driven equipment.

This paper describes a new method to improve efficiency of variable speed drives by power splitting. The main driver is a constant speed motor and its power is transmitted mechanically using the superior efficiency of an epicyclic gear. The gear is designed as revolving planetary gear where all three shafts can turn. One of those shafts is used as input; a second one as output and the third

shaft is used for speed control. This principle allows using only a small percentage of rated power as control power to be generated by servo motors. Their frequency converters are placed in a sideline and hence their losses are subject to a small portion of rated power. The control speed of the servo motors is superimposed in the revolving planetary gear to transform the constant speed of the main motor into a variable output speed for the driven equipment.

A 7500 horse power prototype of an electrically controlled superimposing planetary gear (ESPG) was built and tested extensively. Efficiency measurements were done and could prove peak efficiency of 97 percent for the variable speed gear including lube oil pump, servo motors, frequency converter and transformer. This is up to 2.5 percent more than conventional variable speed systems with a full scale in-line variable frequency drive (VFD).

INTRODUCTION

The reduction of CO_2 emissions has been driving the political and economic agendas all over the world since the United Nations held a conference on Climate Change in Paris end of 2015 (United Nations 2016). With the treaty that entered into force on 4 November 2016, 197 countries agreed on joint efforts to limit the global temperature increase to 2°C (35.6°F) below pre-industrial levels. This implies a sweeping reduction of CO_2 emissions. In addition, environmental regulations and guidelines are continuously being further tightened. Among others, the European standard EN 50598 outlines eco-compatible design requirements for drive systems in electrical driven production machines. Energy markets and the need for a continuous decline in life cycle costs create further challenges for operators and manufacturers of turbomachinery equipment.

As described in U.S. Department of Energy and Hydraulic Institute (2006), centrifugal pumps are often operated over a wide range of conditions. For example, many cooling systems experience variable loads caused by changes in ambient conditions, occupancy, and production demands. Boiler feed pumps have to adapt water flow to the changing demand of steam for power generation. There are five methods for controlling flow through a system or its branches:

- Bypass lines
- Throttle valves
- Multiple pump arrangements
- Impeller trimming
- Pump speed adjustments

The appropriate flow control method depends on the system size and layout, fluid properties, the shape of the pump power curve, the system load, and the system's sensitivity to flow rate changes.

Bypass lines allow fluid to flow around a system component. They provide accurate flow control while avoiding the danger of "deadheading" a pump. Deadheading is the condition in which a pump's flow is completely choked off by closed down-stream valves. A major drawback of bypass valves is their detrimental impact on system efficiency. The power used to pump the bypassed fluid is wasted. In static-head-dominated systems, however, bypass valves could be more efficient than throttle valves or systems with variable speed drives (VSDs). This is shown in figure 1 (U.S. Department of Energy et al., 2006).

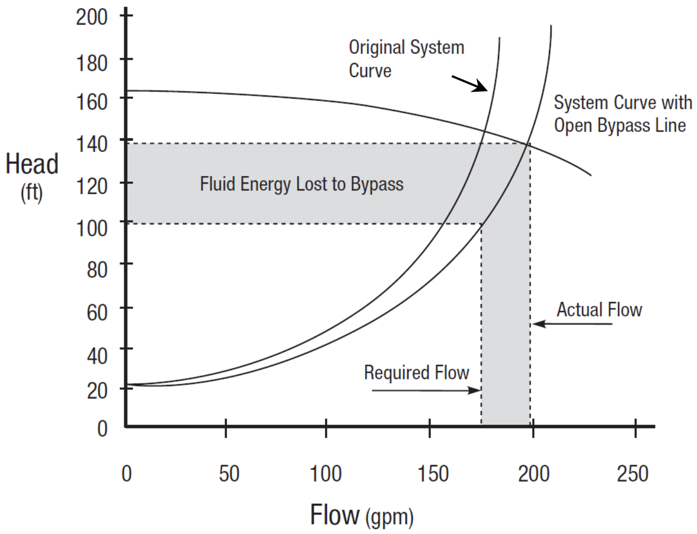

Figure 1. Flow Adjustment by Bypassing a Pump.

A throttle valve chokes fluid flow so that less fluid can move through the valve, creating a pressure drop across it. Throttle valves are usually more efficient than bypass valves, because as they are shut, upstream pressure is maintained and can help push fluid through parallel branches of the system. Throttle valves provide flow control in two ways: by increasing the upstream backpressure, which reduces pump flow, and by directly dissipating fluid energy. By increasing the backpressure on a pump, throttle valves make a pumping system less efficient. In low-static-head systems, variable speed operation allows the pump to run near its best efficiency point (BEP) for a given head or flow as shown in figure 2 (U.S. Department of Energy et al., 2006).

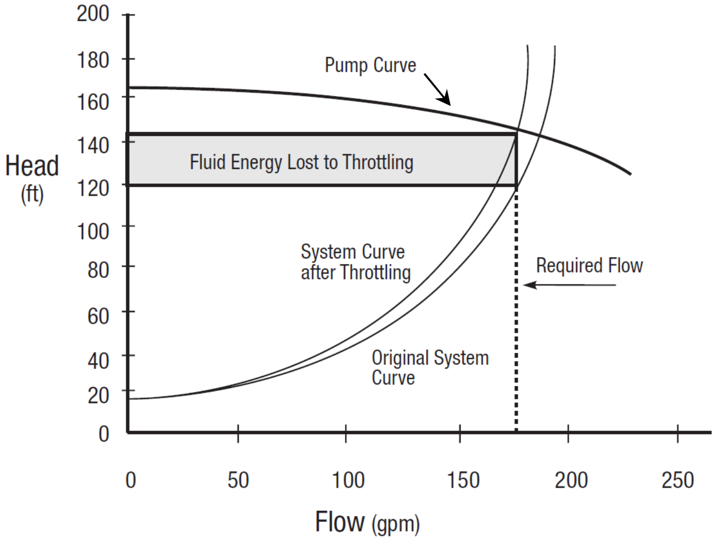

Figure 2. Flow Adjustment by Throttling a Pump.

Multiple pump arrangements typically consist of pumps placed in parallel in one of two basic configurations: a large pump/small pump configuration or a series of identical pumps placed in parallel. In the large pump/small pump case, the small pump, often called the "pony pump," operates during normal conditions. The large pump is used during periods of high demand. Because the pony pump is sized for normal system operation, this configuration operates more efficiently than a system would that relies on the large pump to handle loads far below its optimum capacity. Some of the advantages of multiple pump arrangements are flexibility, redundancy, and the ability to meet changing flow needs efficiently in systems with high static head components. In systems with high-friction components, alternatives such as adjustable speed motors tend to be more efficient solutions to variable demand requirements, see figure 3 (U.S. Department of Energy et al., 2006).

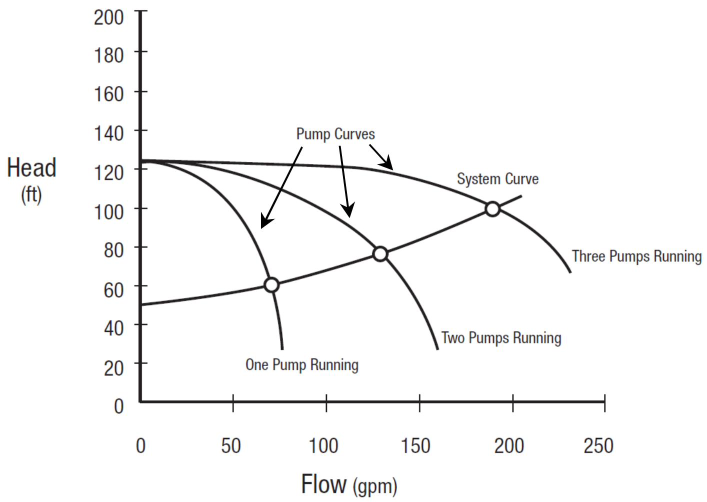

Figure 3. Flow Adjustment by Using Multiple Pump Arrangements.

With a series of identical pumps placed in parallel, the number of operating pumps can be changed according to system demands. Because the pumps are the same size they can operate together, serving the same discharge header. If the pumps were different sizes, the larger pumps would tend to dominate the smaller pumps and could cause them to be inefficient. If the proper pumps are selected, each pump can operate closer to its highest efficiency point. An added flow control benefit of parallel pumps is that a system curve remains the same whether one or several pumps are operating; what changes is the operating point along this system curve.

Multiple pumps in parallel are well suited for systems with high static head. Another advantage is system redundancy; one pump can fail or be taken off line for maintenance while the other pumps support system operation. When identical parallel pumps are used, the pump curves should remain matched; therefore, operating hours should be the same for each pump, and reconditioning should be done at the same time for all of them.

When a smaller impeller is not available or the performance of the next size is insufficient, impeller trimming can be an alternative. Impeller trimming reduces the impeller diameter—and thus the impeller tip speed—so that the same constant-speed pump motor can be used. Since the head generated by a pump is a function of its tip speed, impeller trimming shifts the entire performance curve of the pump downward and to the left. Impeller trimming can be a useful correction to pumps that, through overly conservative design practices or changes in system loads, are oversized for their application. Impeller trimming reduces tip speed, which in turn directly reduces the amount of energy imparted to the system fluid and lowers both the flow and pressure generated by the pump, see figure 4 (U.S. Department of Energy et al., 2006).

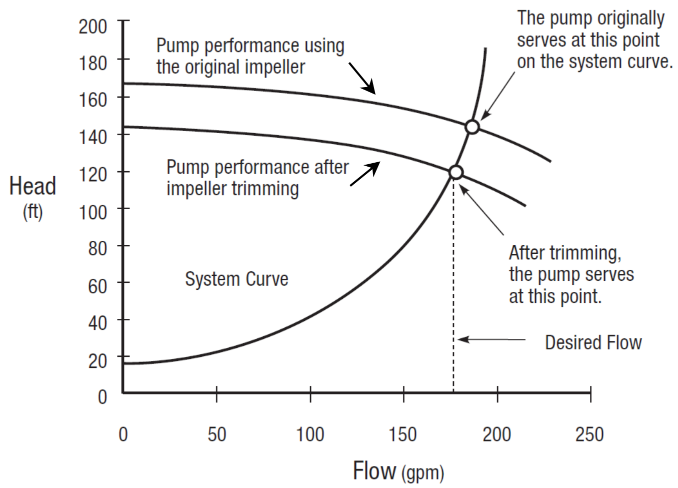

Figure 4. Flow Adjustment by Impeller Trimming.

Pump speed adjustments are the most efficient means of controlling pump flow. Reducing the pump speed means less energy is imparted to the fluid and less energy needs to be throttled or by-passed.

Variable speed drives (VSDs) allow pump speed adjustments to be made over a continuous range, avoiding the need to jump from speed to speed. VSDs control pump speeds using several different types of mechanical, hydrodynamical and electrical systems. Mechanical VSDs include adjustable belts and pulleys, hydraulic systems include fluid couplings, geared fluid couplings and hydrodynamically controlled superimposing planetary gears (HSPG) and electrical VSDs include eddy current clutches, wound-rotor motor controllers and VFDs. VFDs adjust the electrical frequency of the power supplied to a motor to change the motor's rotational speed. The VFDs themselves do also introduce efficiency losses. If normal operation is far below the full load rating of the motor for long operating periods, the cost of these losses can be considerable. A VFD can also introduce harmonics in the motor windings, which increases the winding temperature. Over an extended period of time, this increase in the motor winding temperature accelerates the breakdown of insulation (Hydraulic Institute et al., 2004).

Hydraulic couplings with or without gears are used to transmit power through a fluid. Speed is regulated by changing the oil level in the coupling using a scoop tube. A more efficient way is the use of a superimposing planetary gear (SPG) with a torque converter generating control power. Only a small part of input power is taken out, controlled hydrodynamically and fed back to the main line. This principle has been developed and successfully established in markets, where reliability and long life time under harsh ambient conditions are crucial. Hydrodynamic couplings and a large number of references are described by Voith (2014, 2015).

Pump speed adjustments are not appropriate for all systems, however. In applications with high static head, slowing a pump could induce vibrations and create performance problems that are similar to those found when a pump operates against its shutoff head. For systems in which the static head represents a large portion of the total head, however, operators should use caution in deciding whether to use VSDs. Operators should review the performance of VSDs in similar applications to avoid the damage that can result when a pump operates too slowly against high-static-head conditions (Hydraulic Institute et al., 2004).

Multiple-speed motors contain a different set of windings for each motor speed; consequently, they are more expensive and less efficient than single-speed motors. Multiple-speed motors also lack subtle speed-changing capabilities within discrete speeds.

VSDs, multiple-speed pumps and multiple pump configurations are usually the most efficient flow control options, especially in systems that are dominated by friction head, because the amount of fluid energy added by the pumps is determined directly from the system demand, see figure 5 (U.S. Department of Energy et al., 2006).

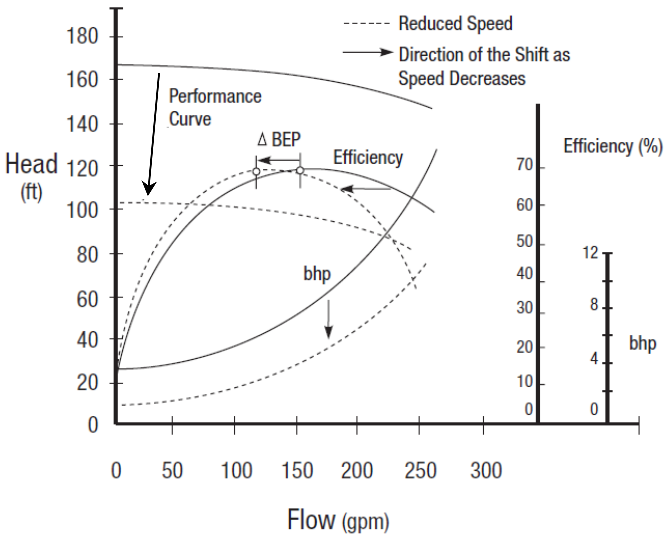

Figure 5. Flow Adjustment by Variable Speed.

Flow control is necessary for many industrial applications and not only for pumps e.g. boiler feed pumps in power plants, but rather compressors e.g. in gas pipelines. As explained by Hanlon (2001) varying the speed of the compressor is an excellent way to control capacity. It will give close, infinite step control, without additional equipment on the compressor. Reduced speed operation is usually easy for the compressor and maintenance intervals may be increased. This method is used with compressors driven by an engine and is increasingly frequent with compressors driven by an electric motor. According to TMEIC Corporation (2011) speed control by turbine engines means:

- Valve throttling losses are avoided
- High speeds can be achieved, which is necessary for boiler feed pumps and axial flow compressors
- The turbine is expensive, especially if it is custom designed
- If a gas turbine is used, there can be air pollution concerns
- Turbine mechanical maintenance can be significant

Many pump motors are driven by variable frequency converters adapting the electric frequency of a three-phase alternating current supply. They are installed in-line and are designed to full power as it is shown in figure 6. Some variable frequency drives need an external transformer, others have an integrated one. However, core losses, eddy current losses and heating losses occur. Depending on the design of a variable frequency drive input filters may be required to satisfy industry standards. Output filters may be required to reduce harmonics and in order to protect standard motors. Both passive and active filters cannot transmit power without generating losses. In some applications, the variable frequency drive is located in some distance from the motor because of its harsh ambient conditions. Then long cables are needed and they produce heating losses. This is described by Siemens (2014) and TMEIC Corporation (2011).

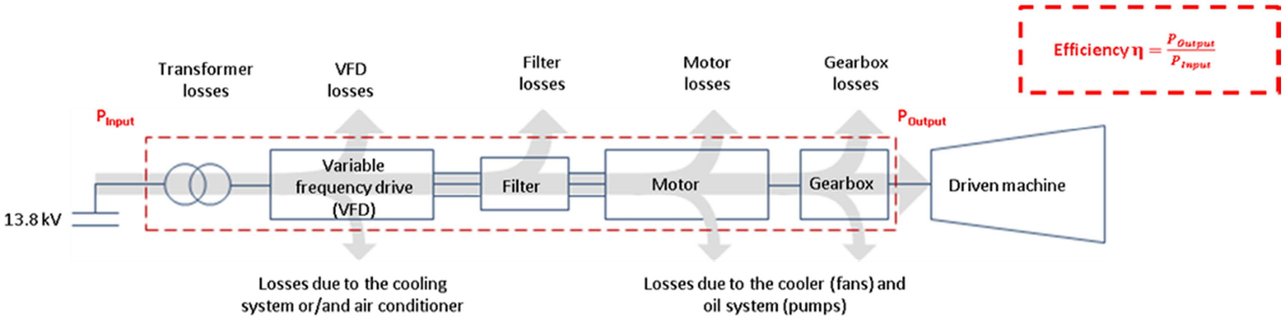

Figure 6. Full Scale In-Line VFD-System.

High speed pumps require a gear to step up the speed out of a standard motor. They have losses caused by toothing, bearings and oil splashing. Since all those components are installed in-line, they transmit full power and their losses are subjected to the complete power flow. An overview of different types of losses is given in table 1. The value ranges represent figures published by TMEIC (2011), Blaiklock (2013) and Siemens (2016).

Component	Efficiency at Rated Speed [%]
Transformer	98.5 – 99.0
VFD	96.5 – 98.0
Filter	≈ 99.0
Motor	95.0 – 98.0
Gearbox	≈ 98.5
Oil System	≈ 99.5
Cooling, Air Conditioning	≈ 99.5

Table 1. Component Efficiencies at Rated Point
(Courtesy of TMEIC, 2011, Blaiklock, 2013 and Siemens, 2016).

This paper presents a new concept of a variable speed drive which is based on power split principle. A superimposing planetary gear (SPG) is used to regulate output speed by adding variable control speed generated by servo motors to constant input speed from the main motor in order to reach a better efficiency than conventional systems today.

FUNCTION AND DESIGN

The SPG is placed between a main motor, typically a four pole medium voltage induction motor and the driven machine, e.g. pump or compressor. It converts the constant input speed to a variable output speed by superimposing a variable speed provided by servo motors. The main motor is directly connected to a medium voltage grid through a main circuit breaker. Standard motors are available for several voltage levels such as 10, 11 or 13.8 kW and can be connected directly to customer's medium voltage line. Therefore, a transformer is not necessary for the main motor. This helps to avoid transformer losses, i.e. core, eddy current and heating losses. The servo motors are designed to a small percentage of rated power and operate on low voltage level. The motors are connected to a variable frequency converter which is fed by a transformer using the same medium voltage line as the main motor. Since the transformer, low voltage frequency converter and servo motors are placed in a side line, their losses are subjected only to a small portion of the rated power. Figure 7 shows the installation of an electrically controlled superimposing gear between a fixed speed motor and a pump or compressor.

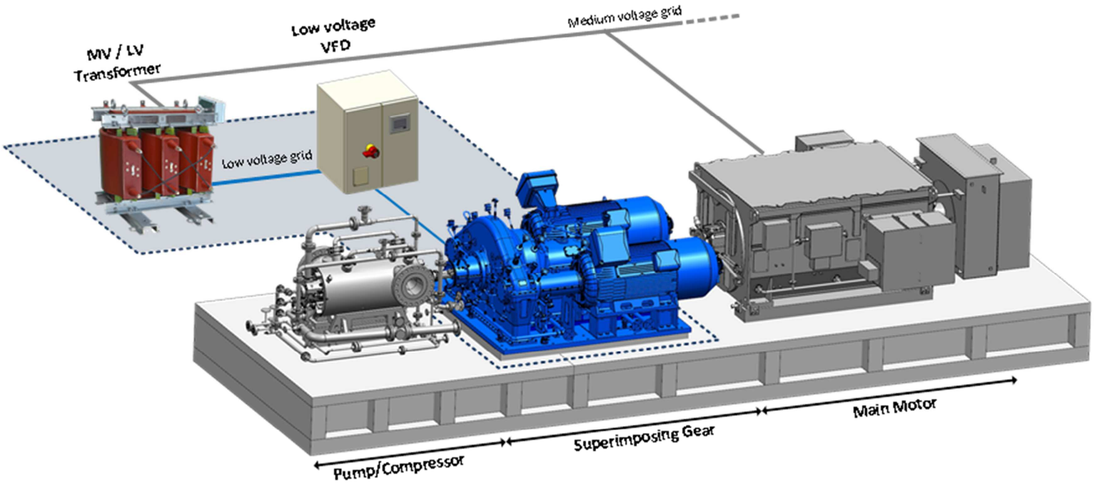

Figure 7. Drive Train with Electrically Controlled Superimposing Gear.

Figure 8 shows the principal design of a SPG. The ring gear of the SPG is connected to input shaft and driven at constant speed. The sun gear is connected to output shaft providing a variable speed to the driven equipment. The planets are supported in a revolving carrier which is driven by two servo motors.

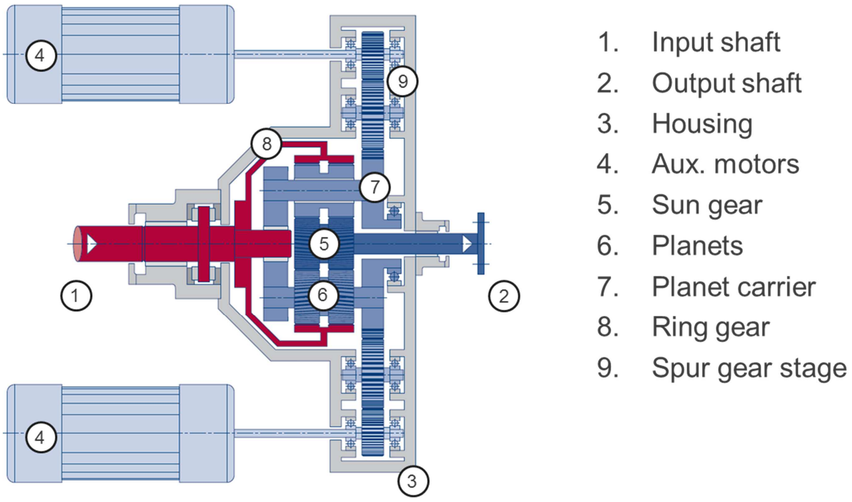

Figure 8. Electrically Controlled SPG.

As shown in Figure 9, planetary gears consist out of a sun wheel, orbited by planets which are supported in a planet carrier. A ring gear encloses all planets. If one of the three shafts, sun, carrier or ring gear is fixed, the two remaining shafts can be used as in- and output building a constant speed ratio. Instead, in a revolving planetary gear all three components are able to turn. The third shaft besides in- and output shaft can be used to superimpose, i.e. to add or deduct another speed. The ring gear is connected to input shaft and turning at constant speed. If the carrier stands still, sun and output shaft turn in opposite directions. To make output speed larger, the carrier has to be driven in the same direction as the sun wheel. To turn down output speed, the carrier has to rotate in the opposite direction to the sun gear.

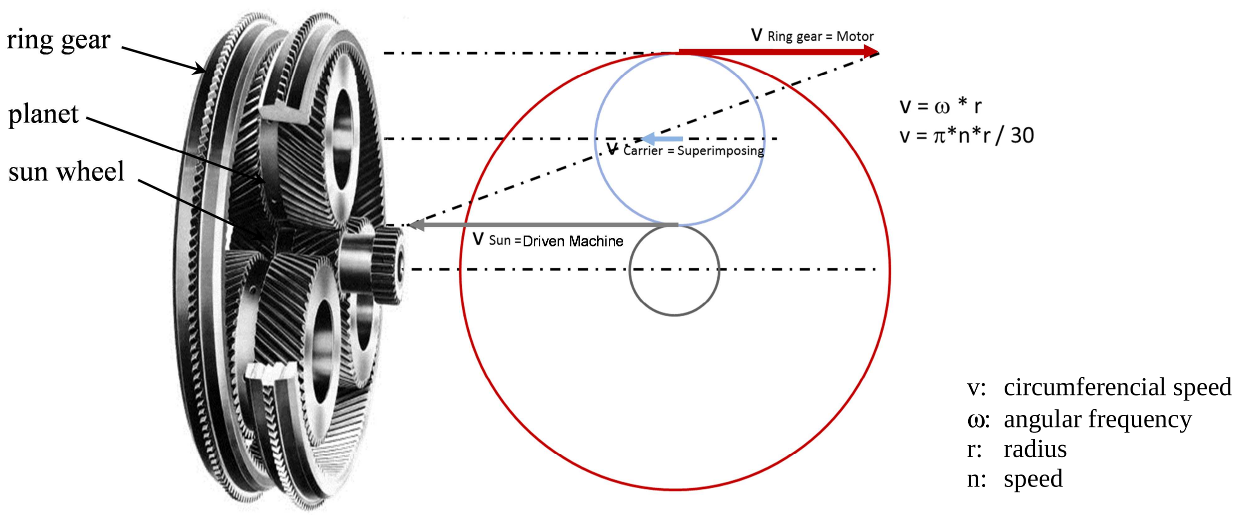

Figure 9. Speed Diagram of a Planetary Gear.

Figure 10 shows the power flow in a revolving planetary gear. The direction of power flow is given by the direction of force/torque and speed/angular speed. In case both act in the same direction, power is added and a drive acts as a motor. If force and speed are opposite, power is taken out of a system and a drive acts as generator. The direction of power flow changes at reversal point (RP). While the output speed is increased, power has to be added to the planet carrier, it is driven. When output speed is turned down, power is taken out of the carrier. This means, the auxiliary machines which are connected to planet carrier act as motor during high speed operation and as generator during at low speed. In generator mode they are able to recuperate power from the drive train and feed it back to the grid. Due to the fact that auxiliary power is added to the train, the main motor becomes smaller.

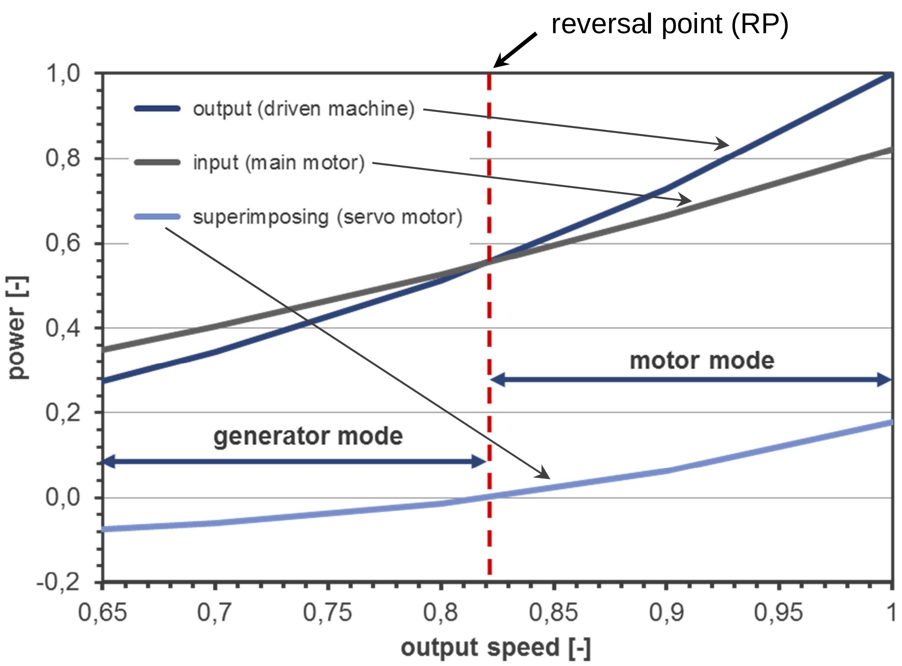

Figure 10. Power Flow in a Superimposing Planetary Gear (SPG).

Figure 11 shows the output torque and superimposing speed versus output speed. Servo motors are to be designed in a way that they provide their maximum power at maximum speed. If the driven equipment is turned down, the speed of servo motors is reduced and also their power to be superimposed in the planet carrier goes down. There is a point, where they stand still. No auxiliary power is needed in this point. The complete output power comes from the main motor and is transmitted purely mechanically. This is the operating condition with peak efficiency. Since the planet carrier and hence the auxiliary motors change their direction of rotation in this point, it is named reversal point (RP). When the output speed has to be further reduced, the auxiliary machines are operated at generator mode.

The required power of the servo motors is influenced by the load characteristic of the driven machine and required speed control range. There are limitations for the system, supporting a high efficient drive system, with a small amount electrical power for speed imposing. Typical compressor applications require a speed control range of 70 – 105 percent of maximum continuous operating speed which results in a power for superimposing of approximately 13 percent. Pump applications requires a speed control range of 50 – 100 percent of rated speed or even larger speed variations. These requirements enlarge the required power of electrical superimposition to 22 percent or even more. A larger portion of electrical superimposing power results in lower efficiency, higher cost for electric servo motors and variable frequency converters compared to systems with a small speed control range.

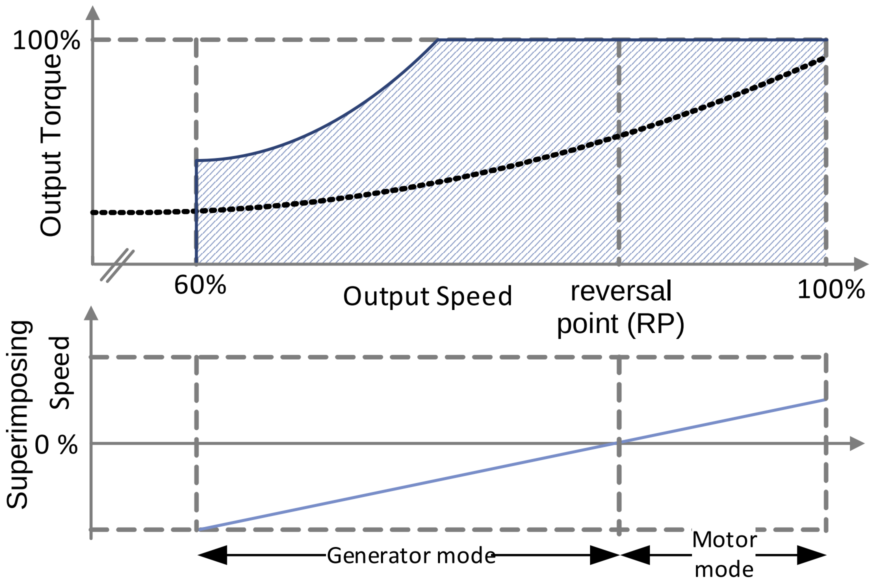

Figure 11. Operating Map of the Driven Machine and Corresponding Servo Motor Speed.

To fulfill the market requirements of an enlarged speed variation range, multiple approaches were investigated by an interdisciplinary team of electrical and mechanical engineers. The mechanical drive train with the planetary gear as a key element allows using the electric servo motors independently to the medium voltage main motor. Transfer of torque in a planetary gear is only possible when one shaft of the drive train is locked or supporting torque on one shaft is provided. The investigations were supported by simulation tools to evaluate different options for additional elements like brake devices, freewheels or clutches. The simulation shows a high potential adding a clutch device that connects input shaft of the planetary gear to the planet carrier.

Figure 12 shows electrically controlled superimposing planetary gear for extended speed variation range. When the input shaft and the planet carrier are mechanically locked, the servo motors are used to operate a driven load without using the medium voltage main motor. Output speeds of 50% or lower are operated without using the main motor, activating the clutch device and using the servo motors in motor mode. This operation mode results in an improved efficiency compared to an electrically controlled superimposing planetary gear without clutch device, because the amount of power that is directly transferred on the mechanical path is increased, and a part load operation of the medium voltage main motor at lower speeds is eliminated.

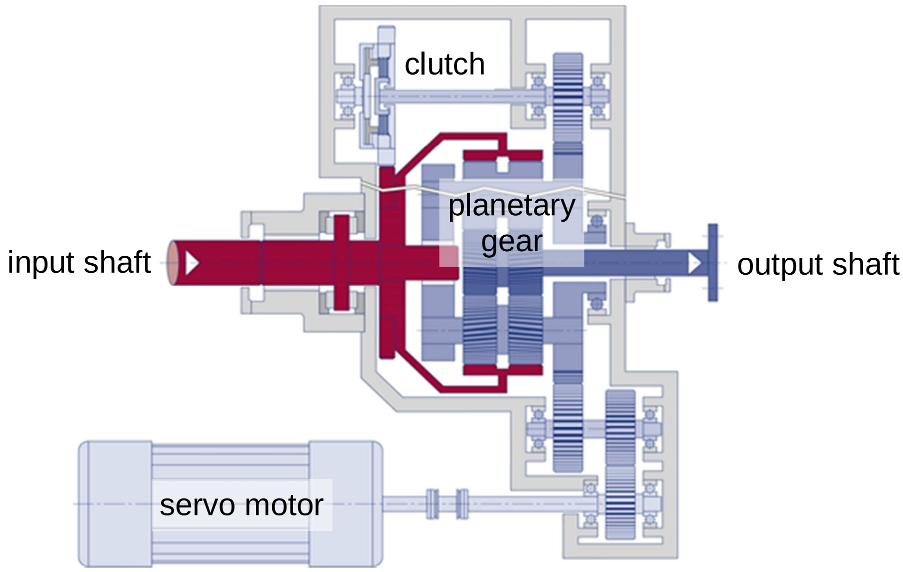

Figure 12. Electrically Controlled Superimposing Planetary Gear (ESPG) for extended Speed Variation.

PROTOTYPE TEST RUN RESULTS

Figure 13 shows a picture of a prototype built to validate the new concept. The first machine was designed for:

- Input speed: 1800 rpm
- Output speed: 7320 – 12200 rpm
- Output power: 5,500 kW
- Size: 3755 x 3649 x 1850 mm (length x width x height)
- Shaft height: 700 mm
- Weight: 17 tons, including base plate, oil reservoir and instrument board

Extensive measurements were done, especially for efficiency evaluation. Mechanical power was measured along the whole speed regulating range at full load as well as part load.

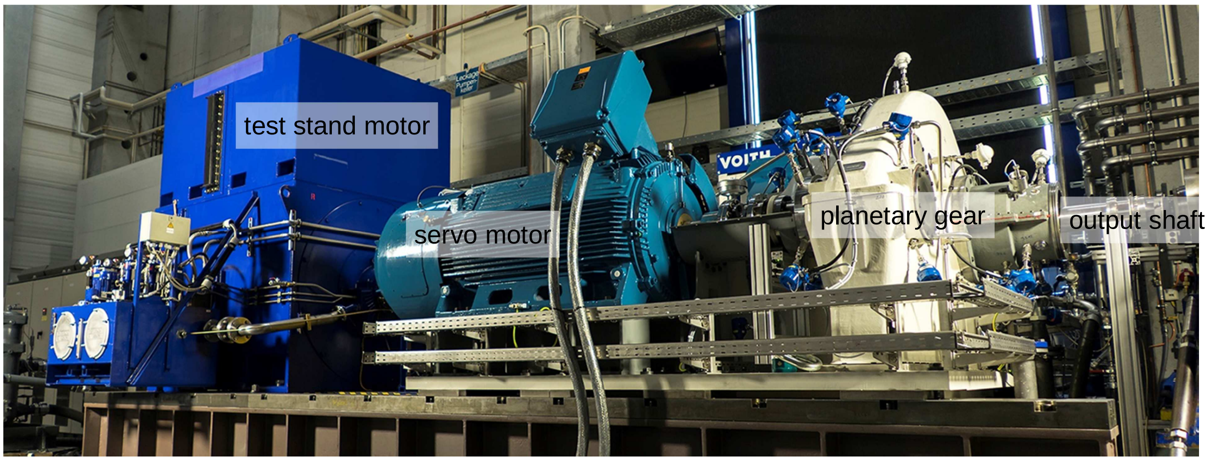

Figure 13. Prototype on a Test Stand.

As shown in figure 14, mechanical power is measured at main input (P_{mech_Input}) and output shaft (P_{mech_Output}). Additionally electric power flow is measured at the low voltage line between transformer and converter ($P_{ele\_LV\_Grid}$). Losses of the medium voltage / low voltage transformer are evaluated by calculation (PV_{Trafo_LV}).

The measurement was executed using calibrated equipment for mechanical and electrical instruments and sensors. All instruments are chosen to achieve a precise result with very low tolerances. All mechanical auxiliaries (e.g. lube oil pump) is driven by the input shaft and their losses are considered in the measurement by using mechanical input and output power. Electrical auxiliaries like cooling fans of variable frequency drive and forced ventilation of the servo motors are supplied by the low voltage grid. Those losses are considered by measuring the power of the low voltage grid.

The mechanical input ($\mathrm{P_{mech\_Input}}$) and output power ($\mathrm{P_{mech\_Output}}$) are evaluated by measuring torque and speed. The torque measurement shafts are make HBM and at input of type T10FM with a range of 0 to +/-60 kNm. The one at output side is of type T40B with a range of 0 to +/-5 kNm. Both torque measurement shafts have been calibrated according to ISO/IEC 17025 using calibration equipment traceable to National Standards according to ISO 9001 and ISO 10012. Their accuracy is +/- 0.1 percent of their nominal value. The speed is measured by using a probe make Rechner type MRS-300-M12-10-S with a digital display unit of type PXI – 6602 make National Instruments covering a range of 0 … 200 kHz. Its maximum error is 0.01 percent in the used range.

The electrical power ($\mathrm{P_{ele\_LV\_grid}}$) was measured by a high accuracy power analyzer able to calculate electrical power from current and voltage. The measurement is done with high performance current transducers make LEM type IT 1000-S/SP1 with a frequency bandwidth from DC up to 500 kHz and a current deviation of -0.001 to -0.003 percent in the used range. The power analyzer of type WT3000 make Yokogawa is proven to work on variable frequency converters with a switched voltage. An error calculation was used to evaluate the maximum error of the efficiency measurement as +/- 0.15 percent of nominal power.

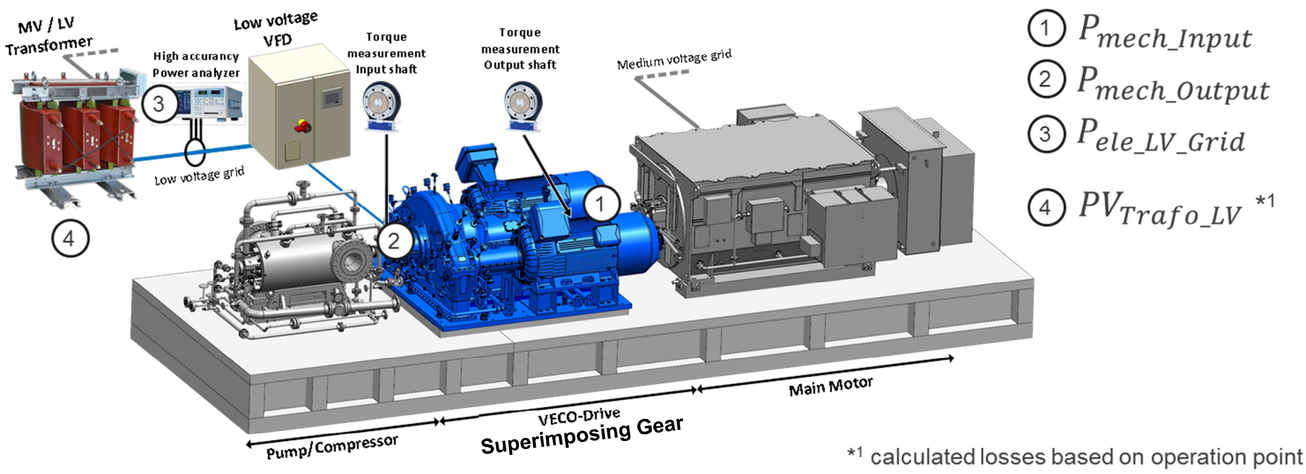

Figure 14. Efficiency Measurement Points in Test System.

Using the measured data the complete component efficiency of the variable speed gear including lube oil pump, frequency converter, transformer and cables can be evaluated as shown in equation (1):

$$\eta = \frac{P_{mech\_Output}}{P_{mech\_Input} + P_{ele\_LV\_Grid} + PV_{Trafo\_LV}} \qquad (1)$$

Figure 15 shows the measured efficiency map as a result of the prototype test run. The peak efficiency which occurs at reversal point is 97 percent. At rated speed the efficiency is still above 96 percent and along a parabolic load curve as this is given by a pump the efficiency for the complete regulating range is above 90 percent.

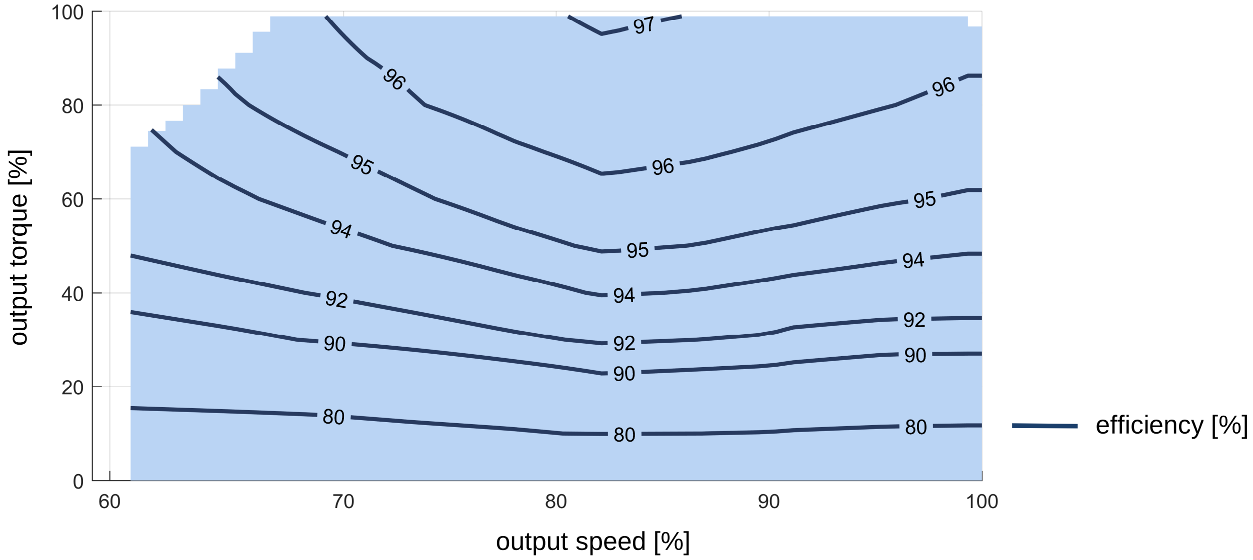

Figure 15. Measured Efficiency Map of Test Unit in Torque versus Speed Graph.

Table 2 lists the efficiency of the various components in a drive train with an in-line full scale frequency converter as it is shown in figure 16.

Component	**Efficiency at Rated Speed [%]**
Transformer	99.0
VFD	97.0
Spur Gear	98.5
Lube Oil System	99.7
Total efficiency	94.3

Table 2. Efficiency of Drive Train Components in a VFD System.

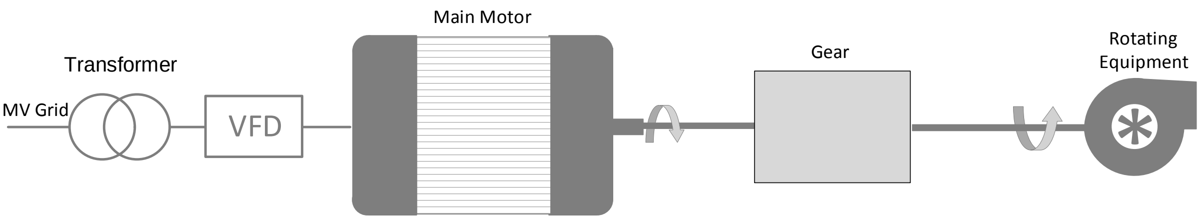

Figure 16. Full Scale In-Line VFD Drive Train.

In figure 17 both efficiency curves are plotted. The dark blue one is that for the values measured on the test stand (uncertainty +/- 0.15 percent). The light grey one shows the calculated efficiency for a full scale in-line VFD using the values from table 1. The electrically controlled SPG is up to 2.5 percent more efficient than an in-line full scale frequency converter.

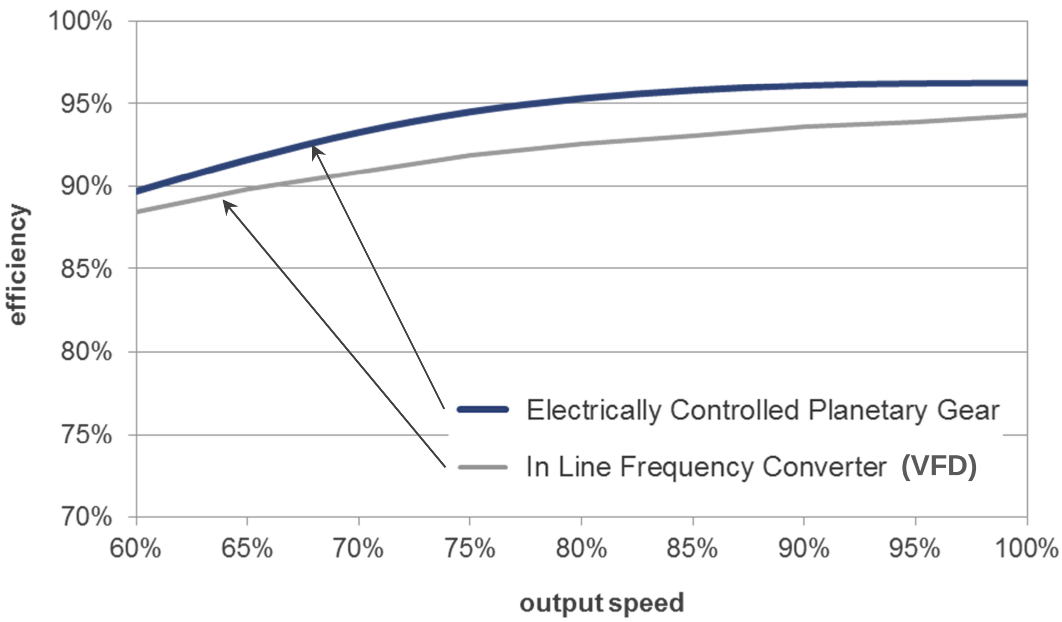

Figure 17. Efficiency Curves.

(VFD)

ECONOMIC ASPECTS

Many hydraulically controlled superimposing gears (HSPGs) are already in use and it is expected that many more electrically controlled superimposing gears (ESPGs) will follow, particularly in applications where a superior efficiency is requested. Most applications for ESPG are expected to be in a range of 5 to 15 MW rated power. The maximum speed of the driven equipment (e.g. compressor) is seen as 15,000 rpm.

CONCLUSIONS

An electrically controlled superimposing gear (ESPG) is an efficient machine for speed control. Variable control speed is generated in a side-line by low voltage frequency converters. Due to the fact that this side-line is only used for a small portion of rated power, losses for variable speed generation are low. The main part of input power is transmitted mechanically through a planetary gear with a superior efficiency which is better than that of a single stage spur gear. A prototype of an ESPG was built and tested extensively. A peak efficiency of 97 percent was measured for all its components between main motor shaft and pump shaft. The efficiency of the test unit is up to 2.5 percent higher than that of full scale in-line variable frequency systems.

NOMENCLATURE

AFD	Adjustable Frequency Drive
BEP	Best Efficiency Point
DC	Direct Current
ESPG	Electrically Controlled Superimposing Planetary Gear
HSPG	Hydraulically Controlled Superimposing Planetary Gear
MV	Medium Voltage
RP	Reversal Point
SG	Superimposing Planetary Gear
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
VSI	Voltage Source Inverter

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